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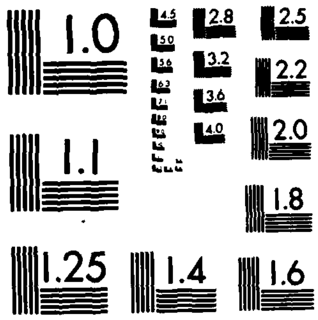

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A Probabilistic Model for Predicting the Duration of Levels of Electromagnetic Transmission in Falling Snow

ROSEMARY M. DYER

AD-A143 318

3 February 1984

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The increasing use of short wavelengths in systems required to operate in all weather conditions under battlefield environments requires that a commander in the field be able to predict the performance of these systems in the short term. A particular problem is the performance of millimeter and micrometer wavelengths in falling snow.

This report presents a predictive model based on the assumption that the transmission like the snowfall intensity, behaves as a Markov chain. The model was developed from data acquired during the SNOW-ONE-A field

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program, and was tested for a hypothetical weapon system operating in the 8-12 micrometer band. The agreement of theory with measurements is excellent, but the model requires further testing on actual systems.

Preface

The author wishes to thank all the participants of SNOW-ONE-A, cited in the references, who made their data available. Special thanks go to Keith Roberts of DPSI, for solving the problem of entering data originally recorded on an HP-9825 into the mainframe computer at AFGL. Finally, thanks are to James Willand of SASC for his programming efforts, and to Dick Jones and his associates in AFGL's technical illustration section.

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1. INTRODUCTION

There has been, in recent years, a steady increase in the use of the shorter wavelengths in the electromagnetic spectrum for Air Force navigation, guidance, surveillance, weapon, and control systems. This in turn has created a demand for more precise and more accurate predictions of the behavior of these systems under all weather conditions, particularly in cloud, fog, or precipitation. In general, the response to these demands has been in the form of greater efforts to characterize the hydrometeors affecting electromagnetic transmission, and to develop mathematical models consistent with physical laws relating the appropriate meteorological parameters with their effects on transmission at the appropriate wavelengths. An outstanding example of such models is the library of computer programs compiled by the Army's Atmospheric Sciences Laboratory in White Sands, New Mexico.[1] These programs have distilled the results of theoretical studies and field programs performed by several military and civilian research teams.

(Received for publication 3 February 1984)

1. U.S. Army Atmospheric Sciences Laboratory, White Sands, New Mexico, 1982. EOSAEL-82 (Electro-Optical Systems Atmospheric Effects Library - 1982. Version). In five volumes: I Executive Summary, II and III, Natural and Battlefield Aerosols, IV Radiative Transfer and Turbulence, V User's Guide. Also, a supplement giving program listing and computer code. ASL-TR-0122. (Available only to government agencies and their contractors.)

The most obvious shortcoming of elaborate mathematical-physical models is that they often require measurements of meteorological parameters not normally available in the battlefield, or measurements of standard meteorological quantities at prohibitively short time and space intervals. A response to this objection is the suggestion that estimates of the pertinent meteorological parameters can be made behind the front lines, using all available data sources, and then either these parameters or estimates of propagation characteristics can be transmitted to the commander in the field. This suggestion is not completely satisfactory, ignoring as it does the problem of communications security and the near saturation of communications facilities that inevitably exists during battle conditions.

Another drawback to the use of elaborate models for predicting transmission conditions is that they usually fail to address directly the questions a commander in the field must have answered before he can make a knowledgeable decision. When confronted with adverse weather conditions that hamper operations on the battlefield, a commander is less interested in why conditions are as they are, than he is in an immediate, reliable answer to the question "How long will this situation continue?". A corollary question, given that conditions are favorable at the moment, or that they will probably become favorable within a given time interval, is "How long will we be able to operate before weather conditions force us to discontinue?". In the past, the answer to both questions could often be found in a detailed local meteorological forecast. However, that no longer suffices. Forecasts of electromagnetic transmission conditions must take into account the wavelength at which the system operates, the initial signal strength, the acceptable received signal strength, and the distance over which the transmission occurs.

If a modification of some mathematical-physical model such as EOSAEL-82 is used, the prediction must be made in two stages. First, the user would key in the appropriate parameters of the system, and the computer would produce critical threshold values of the (one or more) meteorological quantities affecting the transmission. Most mathematical models are designed to produce the inverse. Given the meteorological parameters, EOSAEL-82 (for example) will compute the transmission coefficient as a function of frequency. At the second stage, the meteorologist will predict the elapsed time before the threshold values are reached, and the duration over which they will remain at or below (above) those critical values.

This implies that the relation between the physical parameter and transmission is unambiguous enough to permit the predictor and the predictand to be interchanged. Such is not the case when the phenomenon in question is falling snow, particularly as it affects transmission of micrometer waves. Both measurements in the field and theoretical studies[2,3,4] indicate that, while there exists a relationship between the snowfall rate (or more exactly, amount of snow in the air) and the attenuation of electromagnetic waves, this relation is complicated by other factors, including but not necessarily limited to, snow crystal type and density, ambient temperature and wind, and the snow particle size distribution. An alternative method must be devised to answer the questions posed above by a commander whose systems are hampered by falling snow.

The model described in this report predicts the duration of critical transmission levels of millimeter and micrometer waves in falling snow. It can be used by any field commander who has access to standard meteorological data and predictions. The snow situation must be predicted, and classified according to the three broad categories described in Section 2. 3. The fluctuations in transmission during a snowfall are treated as a Markov Chain. The theory behind the model is presented in Sections 2. 1 and 2. 2. Data from the SNOW-ONE-A program[4] were used to develop the model, as described in Section 2. 3. The application of the model to a specific system is given in Section 3.

2. PROBABILISTIC MODEL FOR TRANSMISSION IN FALLING SNOW

2.1 The Persistence Hypothesis

An implicit assumption underlying any mathematical model of the effect of falling snow on electromagnetic transmission states that, regardless of wavelength, the attenuation is proportional to some measure of the amount of snow in the air. This may be estimated by snowfall rate, or more explicitly by the mass of snow per unit volume of air. This assumption, stated in the broadest terms, is simply that if the amount of snow in the air increases, the attenuation will also increase, all other parameters being held constant.

Snowfall rates measured at the ground and recorded at fixed time intervals are not completely independent variables, but exhibit the type of persistence characteristic of a Markov chain.[5] That is, the intensity at one time is dependent only upon

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2. Redfield, R.K., Ed. (1982) SNOW-ONE Preliminary Data Report, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
3. U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1981 Proceedings, Snow Symposium I.
4. Aitken, G.W., Ed. (1982) SNOW-ONE-A Data Report, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, Special Report 82-8.
5. Dyer, R.M. (1970) Persistence in snowfall intensities measured at the ground, J. Appl. Meteorol. 9:29-34.

the intensity at the previous time interval. If the attenuation of electromagnetic waves is a function of the snowfall intensity, it is reasonable to assume that the transmission will also exhibit some degree of persistence. Such an assumption will permit us to predict future transmission conditions in the short term by assuming that the attenuation values vary as a Markov chain. This is a far less stringent assumption than any physical model which assumes that the relations between the transmission and the measured meteorological parameters remain unchanged during the storm and from storm to storm.

The persistence hypothesis underlying the probabilistic model derived here can be stated as follows:

> For any wavelength, the attenuation at any instant depends only on the attenuation at the previous instant, and the correlation between the attenuation measured at successive, equally-spaced time intervals remains constant throughout the transmission period.

2.2 Derivation of a Markov Model [6]

Divide the possible attenuation levels into N categories. The probability that the attenuation will move from level k to level m in the next time interval is P_{km}. This is known as the transitional probability. The probability matrix for this situation is

$$\underline{P} = \left| \begin{array}{cccccccc} p_{11} & p_{12} & p_{13} & p_{14} & p_{15} & p_{1m} & \cdots\cdots & p_{1N} \\ p_{21} & p_{22} & p_{23} & p_{24} & p_{25} & p_{2m} & \cdots\cdots & p_{2N} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{k1} & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{N}^{1} & P_{N2} & p_{N}^{3} & p_{N}^{4} & p_{N5} & p_{Nm} & \cdots\cdots & p_{NN} \end{array} \right| . \tag{1}$$

Under the Markov assumption, the probability that the attenuation will be at level m after n time steps, given that it started at level k, is found by looking at the kth row, mth colum of the matrix $\underline{P}^n$, where

$$\underline{P}^n = \left| P \right|^n . \tag{2}$$

6. Karlin, S., and Taylor, H. M. (1981) A Second Course in Stochastic Processes, New York, Academic Press, xviii + 542 pages.

When N is larger than 4 or 5, the computation of $\underline{P}^n$ can soon become very unwieldy. Sometimes simplifying assumptions can be made, such as that $P_{km} = 0$ if $|k - m| > 1$. Unfortunately, this was not found to be the case when data from SNOW-ONE-A field program were analyzed.[7] However, there is a simple way to test the validity of the assumption. If we consider only the diagonal of the matrix, we obtain the probability of persistence of the attenuation in any one category.

A test can also be made of the assumption that the transmission, like the snowfall intensity, varies as a Markov chain. Both these tests were applied to the SNOW-ONE-A data, and will be discussed in the following sections.

2.3 Implementing the Model

The data used here were all obtained during the SNOW-ONE-A field program at Camp Ethan Allen, Vermont, between December 1981 and February 1982. The synoptic weather conditions as reported by M. A. Bilello of CRREL[8] were used to classify the storms into three types. Propagation measurements made by a team from the Ballistic Research Laboratory[9] at millimeter wavelengths and by J. Curcio of the Naval Research Laboratory[10] at micrometer wavelengths were used to derive duration statistics, as were available measurements of airborne snow concentration by J. Lacombe of CRREL.[11]

It was immediately apparent that the first step necessary would be to classify the storms, or segments of storms according to the wind velocity and the snowfall intensity. Consulting Bilello's report, and referring on occasion to meteorological conditions at the site as reported by R. Bates[12] resulted in the division of the data according to three storm types.

Type A	Light snow. Hourly accumulations small. (< 0.02 in. of water equivalent per hour.) Visibility 1.6 km or better. Wind not a factor.
Type B	Wind gusts exceed 10 mps. Visibility affected by blowing, as well as falling snow.
Type C	A well developed system with steady, occasionally heavy snow. (Measured accumulation up to 0.08 in. of water equivalent per hour.)

In the present analysis, three storms with a total of 28 hours of data were classified as Type A, three storms totalling 26 hours were Type B, and two storms with a combined duration of 28 hours were classified as Type C.

(Due to the large number of references cited above, they will not be listed here. See References, page 33.)

As a test of the applicability of the Markov hypothesis to the transmission data, the transmission data in Reference 10 for the 8-12 μm band were analyzed to yield the autocorrelation coefficient curve and the power spectrum. Then, a filter successfully used previously[13] was applied to the r: · data, and the autocorrelation coefficient power spectrum curves were recalculated, using the modified data. The filter is a simple red-noise filter of the form

$$X_i = Y_i - \rho\, Y_{i-1} \qquad (3)$$

where Y_i and Y_{i-1} are the original values of the transmission at time i and i - 1, respectively, ρ is the autocorrelation of the Y's at the first time lag, and X_i is the new, modified value of the transmission at time i.

The results of this are shown in Figures 1 through 3. In Figure 1a, the autocorrelation coefficient and power spectrum typical of Type A storms, unmodified data, are given. The slowly decreasing autocorrelation coefficient, and the clustering of the power near zero frequency are all characteristics of a Markov process. Figure 1b shows the autocorrelation coefficient and power spectrum of the modified data. In this case, the autocorrelation coefficient drops very rapidly to zero, and the power spectrum shows that the residual exhibits some periodicity. This is very similar to results obtained by applying the filter of Eq. (3) to snowfall data in Montreal, when the storms were also Type A storms.[5]

Figures 2a and 2b show the same analysis for Type B storms, and Figures 3a and 3b give the results for Type C storms.

The propagation data were then transformed into units of dB/km, and each measurement was placed into one of twenty classes. The class width was 0.5 dB/km, Class 1 being < 0.5 dB/km, and Class 20 > 9.5 dB/km. The data were sampled at 1-min intervals, which was the recording interval for the micron wave data. The millimeter wave data were interpolated linearly to obtain 1-min data. This was practical only when there was little change from one measurement to another, and it was not possible to extend the analysis of the millimeter data to include the computation of transitional probabilities. The snow mass data were also grouped into classes, the width of each class being 0.1 g/m^3, with Class 1 being < 0.1 g/m^3. Altogether, there were eight frequencies or frequency bands analyzed.

13. Dyer, R.M. (1971) Method for filtering meteorological data, Monthly Weather Review 99:435-438.

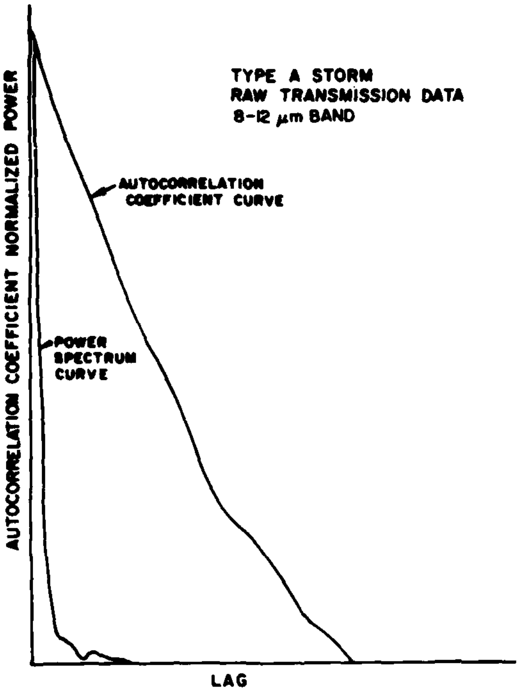


Figure 1a. Autocorrelation Coefficient Curve and Power Spectrum Curve of the Transmission Data in the 8-12 μm Band—Type A Storms

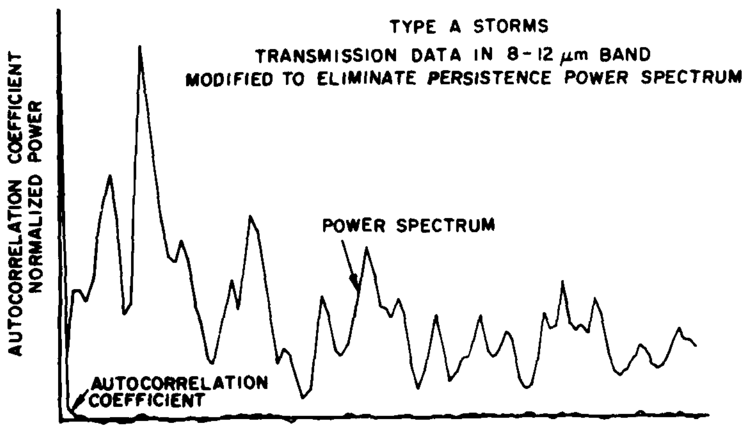


Figure 1b. Autocorrelation Coefficient Curve and Power Spectrum Curve of the Transmission Data After Modification to Eliminate Persistence—Type A Storms

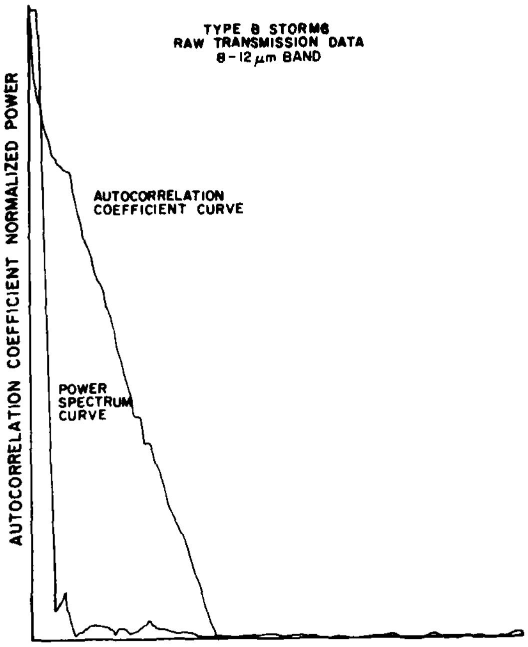


Figure 2a. Autocorrelation Coefficient Curve and Power Spectrum Curve of the Transmission Data in the 8-12 μm Band—Type B Storms

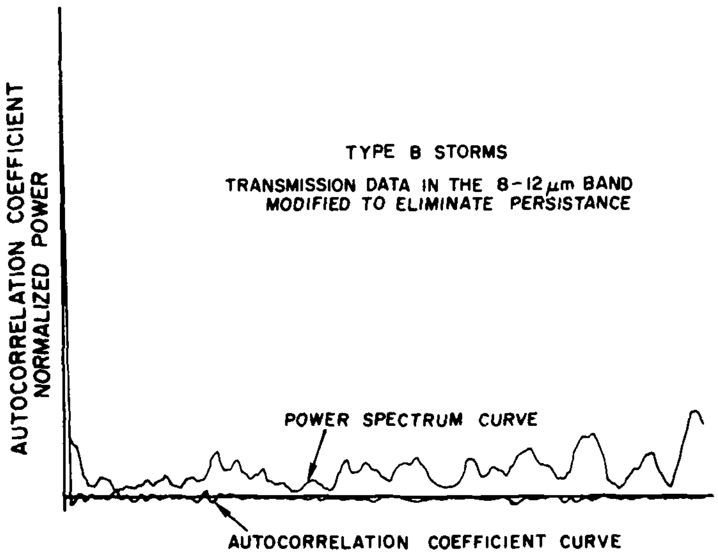


Figure 2b. Autocorrelation Coefficient Curve and Power Spectrum Curve of the Transmission Data After Modification to Eliminate Persistence—Type B Storms

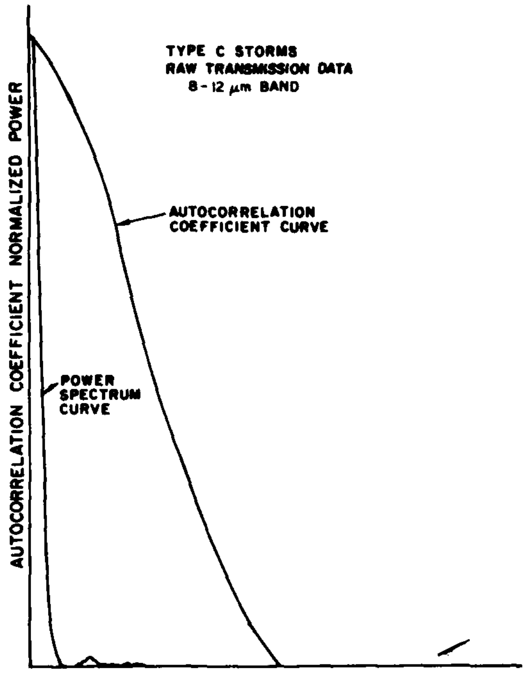


Figure 3a. Autocorrelation Coefficient Curve and Power Spectrum Curve of the Transmission Data in the 8-12 μm Band—Type C Storms

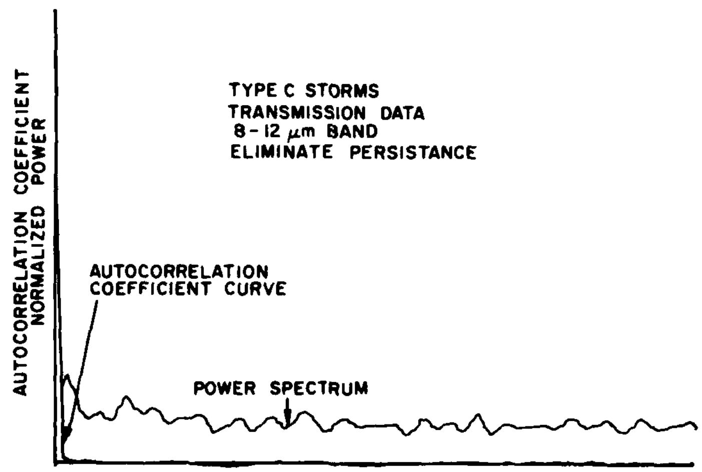


Figure 3b. Autocorrelation Coefficient Curve and Power Spectrum Curve of the Transmission Data After Modification to Eliminate Persistence—Type C Storms

Figure 4 shows the persistence of snow mass density 0.1 g/m^3 during Type A storms, and demonstrates the high degree of persistence found in previous studies of snowfall data.[5] The curves shown in Figures 5 through 12 indicate the persistence of attenuations less than 0.5 dB/km during Type A snowfalls. It should be noted that these low attenuations constitute the bulk of the measurements taken during Type A storms, which were characterized by light snowfall rates, small total accumulations of liquid water equivalent, and negligible winds. There is a high degree of persistence in all these curves.

The measured duration statistics for attenuations less than 0.5 dB/km during Type B storms are presented in Figures 13 through 20. Measurements of snow density varied so much during these storms, which were characterized by high winds, that no meaningful duration statistics could be extracted. The main contrast between these curves and their counterparts for Type A storms is the rapid decrease in the probability-duration curve in the 0.55 μm and in the 3-5 μm band (Figures 13 and 15).

Statistics for Type C storms (well-developed storm systems, moderate to heavy accumulations of snow, wind not a factor) are shown in Figures 21 through 35. In Figures 22, 23 and 24, two curves are shown, one for the attenuations less than 0.5 dB/km. The duration-probability curves for the intermediate attenuation levels lie within the two extremes illustrated. In these cases, the higher attenuations persist longer than the low attenuations. For Figures 25 through 29 as in the previous figures, when there is a single curve, it is for attenuations less than 0.5 dB/km, or for snow density less than 0.1 g/m^3.

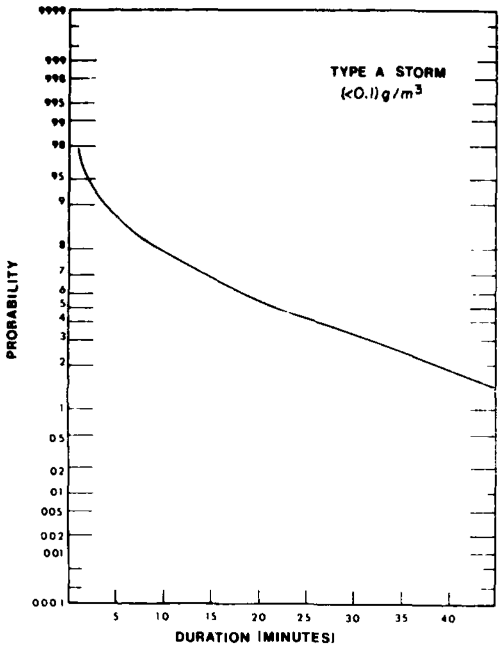


Figure 4. Observed Probability-Duration Relation During Type A Storms of Snow Mass Density Less Than 0.1 g/m^3

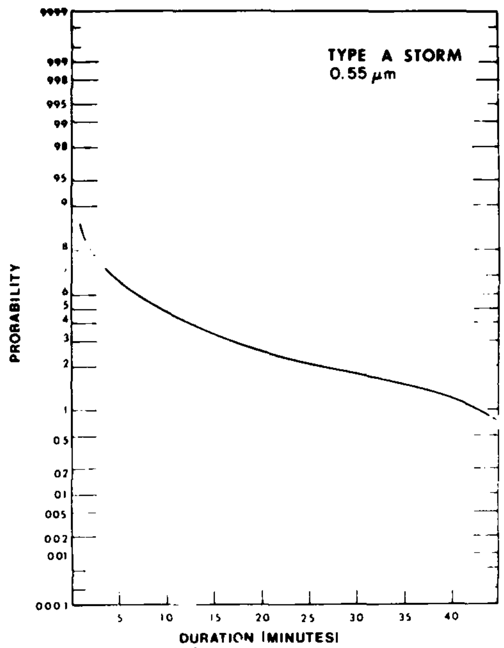


Figure 5. Observed Probability-Duration Relation During Type A Storms of Attenuation Values Less than 0.5 dB/km for Wavelength = 0.55 μm

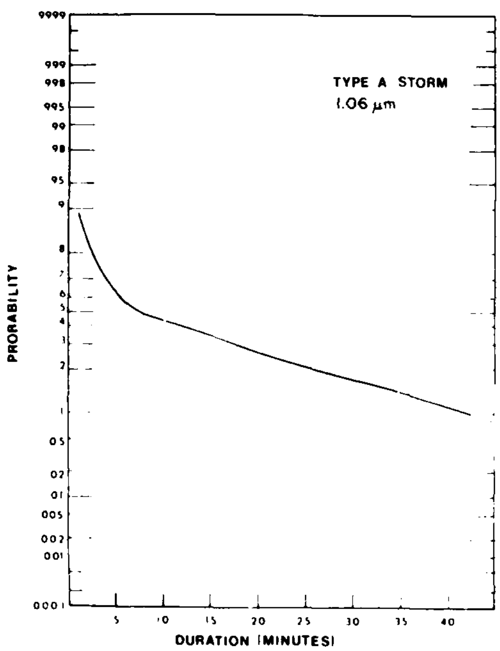


Figure 6. Observed Probability-Duration Relation During Type A Storms of Attenuation Values Less than 0.5 dB/km for Wavelength ± 1.06 μm

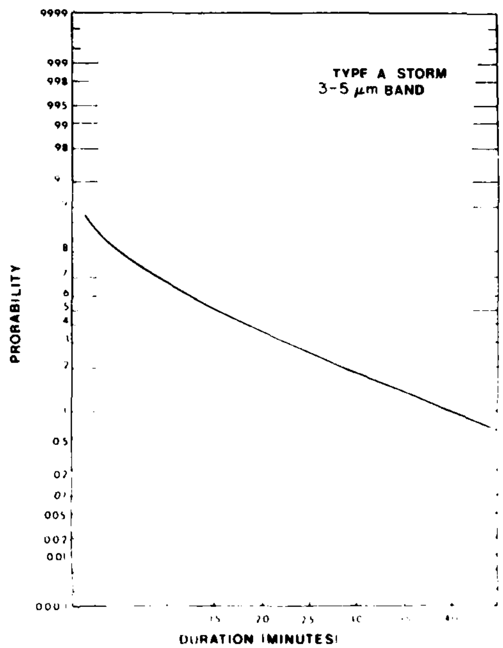
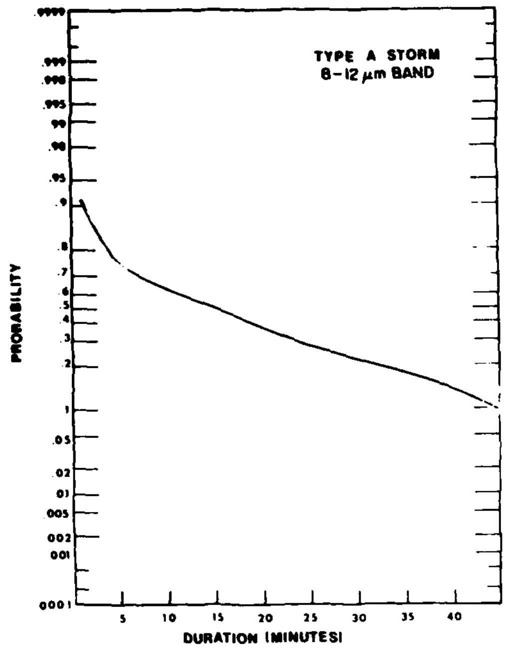


Figure 7. Observed Probability-Duration Relation During Type A Storms of Attenuation Values Less than 0.5 dB/km for the 3-5 μm Band



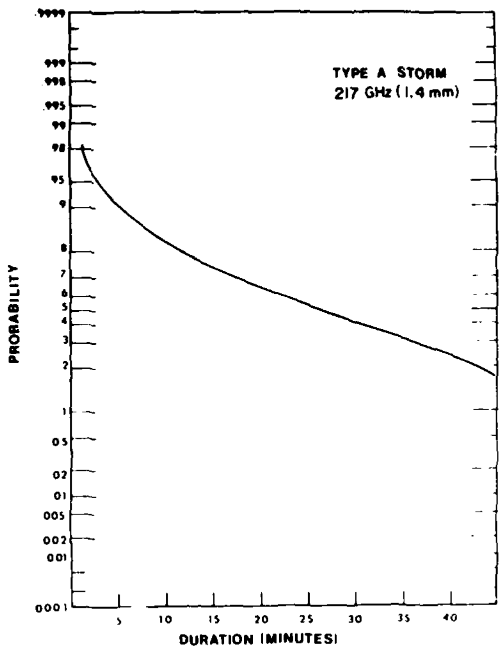
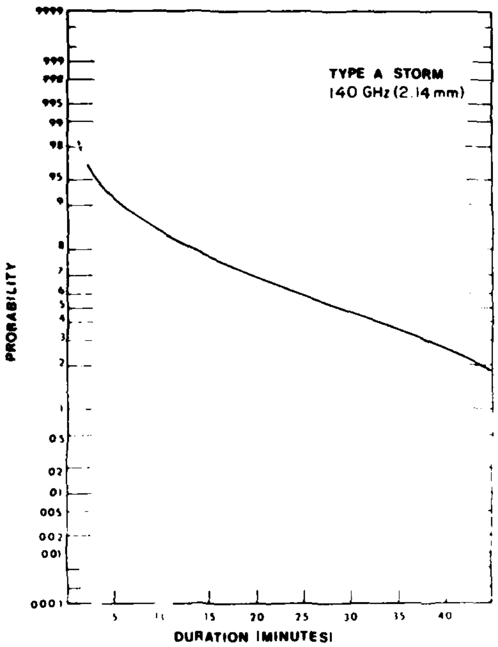


Figure 8. Observed Probability-Duration Relation During Type A Storms of Attenuation Values Less than 0.5 dB/km for the 8-12 μm Band

Figure 9. Observed Probability-Duration Relation During Type A Storms of Attenuation Values Less than 0.5 dB/km for 217 GHz (1.4 mm)



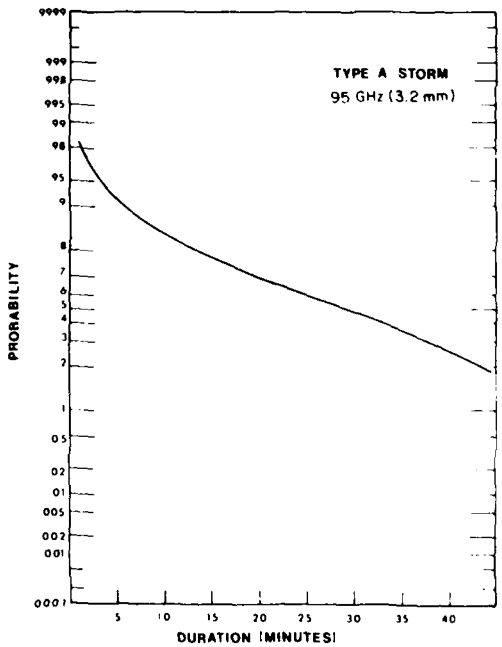


Figure 10. Observed Probability-Duration Relation During Type A Storms of Attenuation Values Less than 0.5 dB/km for 140 GHz (2.1 mm)

Figure 11. Observed Probability-Duration Relation During Type A Storms of Attenuation Values Less than 0.5 dB/km for 95 GHz (3.2 mm)

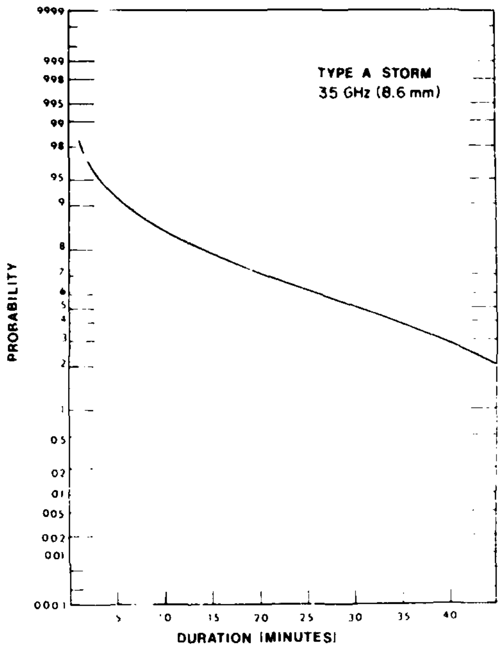


Figure 12. Observed Probability-Duration Relation During Type A Storms of Attenuation Values Less than 0.5 dB/km for 35 GHz (8.6 mm)

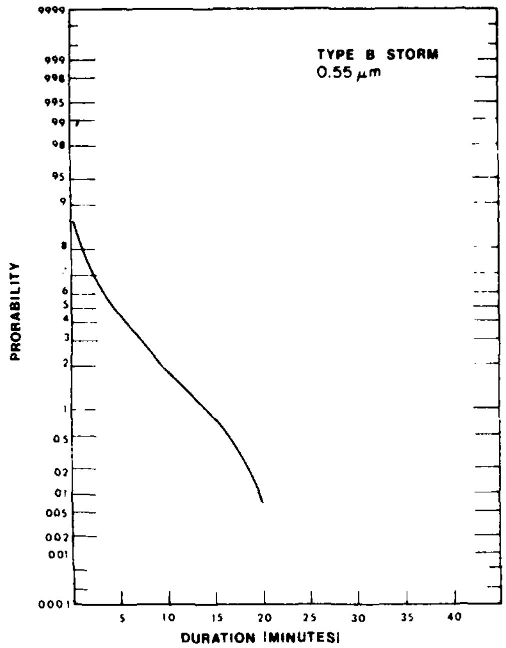


Figure 13. Observed Probability-Duration Relation During Type B Storms of Attenuation Values Less than 0.5 dB/km for Wavelength = 0.55 μm

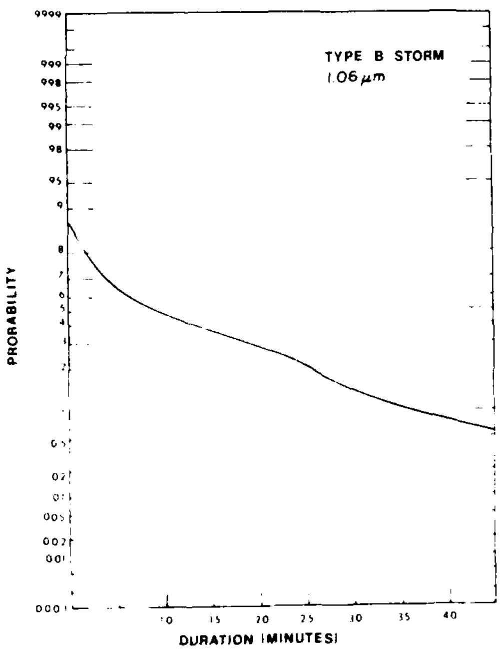


Figure 14. Observed Probability-Duration Relation During Type B Storms of Attenuation Values Less than 0.5 dB/km for Wavelength = 1.06 μm

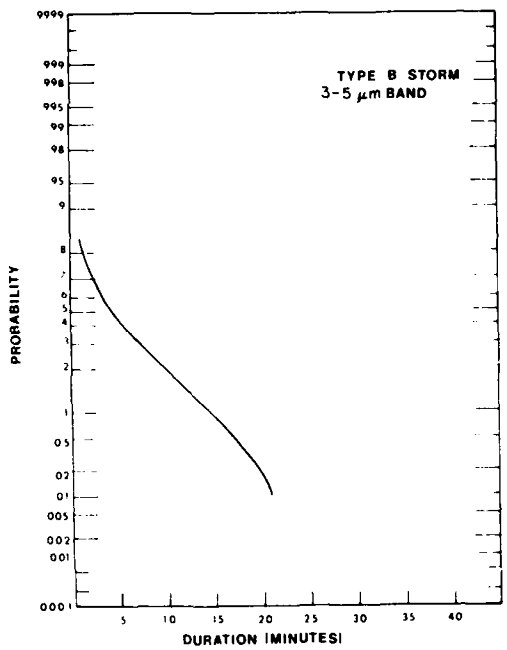


Figure 15. Observed Probability-Duration Relation During Type B Storms of Attenuation Values Less than 0.5 dB/km for the 3-5 μm Band

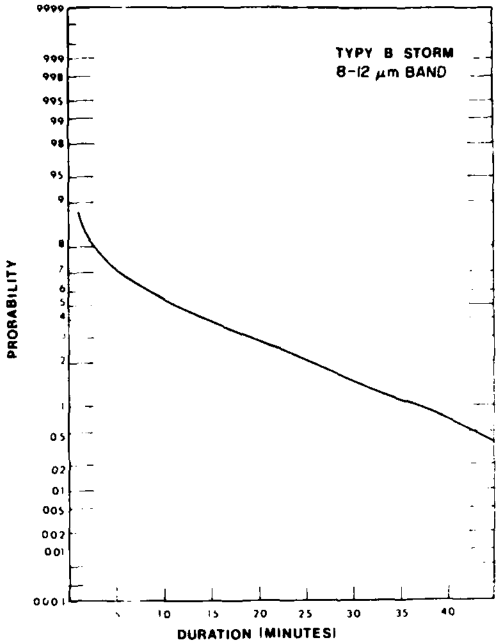


Figure 16. Observed Probability-Duration Relation During Type B Storms of Attenuation Values Less than 0.5 dB/km for the 8-12 μm Band

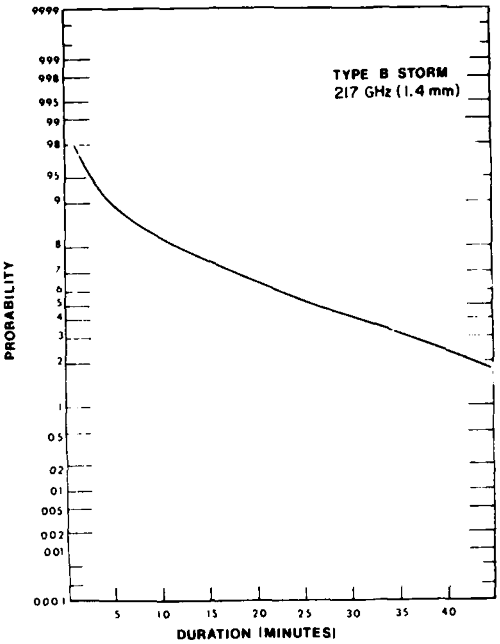


Figure 17. Observed Probability-Duration Relation During Type B Storms of Attenuation Values Less than 0.5 dB/km for 217 GHz (1.4 mm)

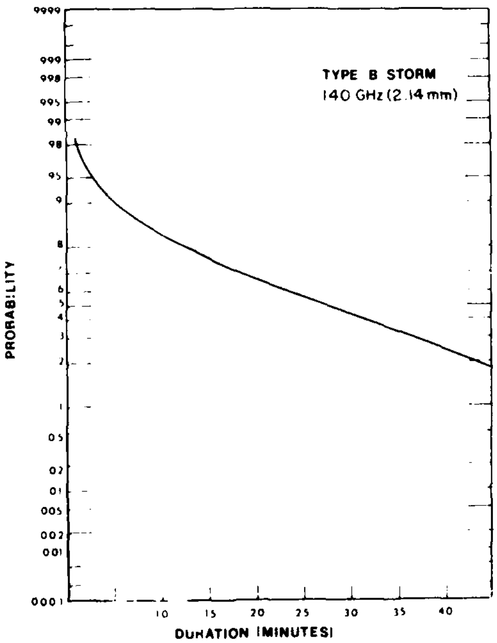


Figure 18. Observed Probability-Duration Relation During Type B Storms of Attenuation Values Less than 0.5 dB/km for 140 GHz (2.1 mm)

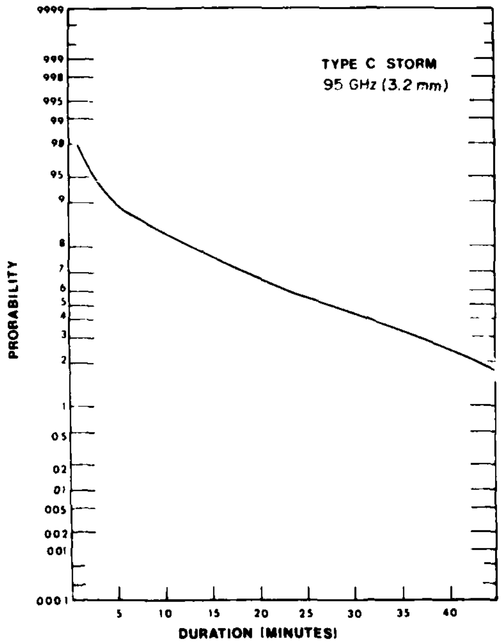


Figure 19. Observed Probability-Duration Relation During Type B Storms of Attenuation Values Less than 0.5 dB/km for 95 GHz (3.2 mm)

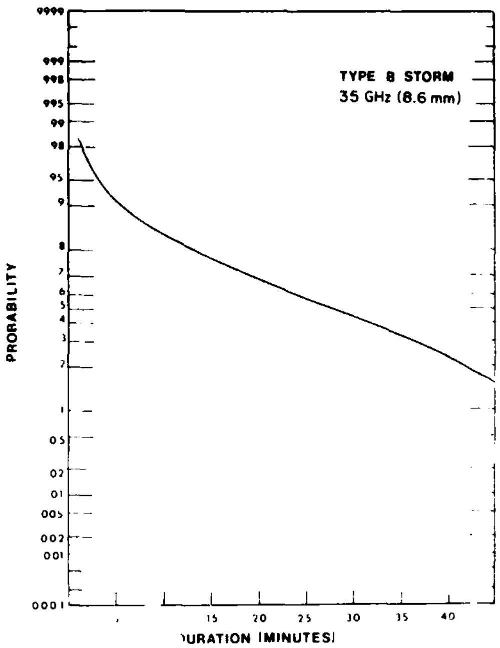


Figure 20. Observed Probability-Duration Relation During Type B Storms of Attenuation Values Less than 0.5 dB/km for 35 GHz (8.6 mm)

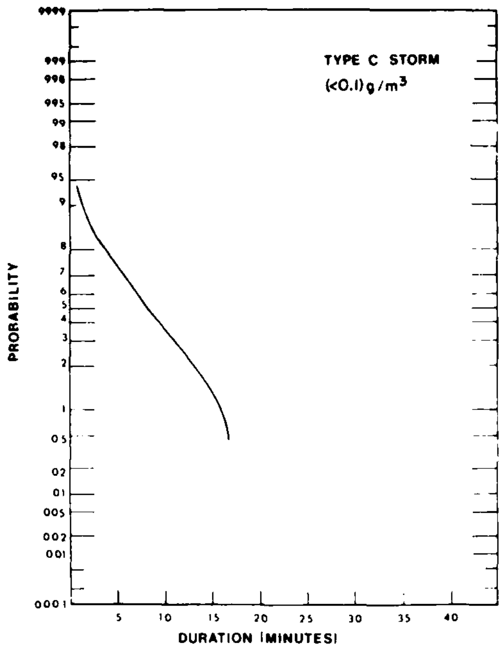


Figure 21. Observed Probability-Duration Relation During Type C Storms of Snow Mass Density Less than 0.1 g/m^3

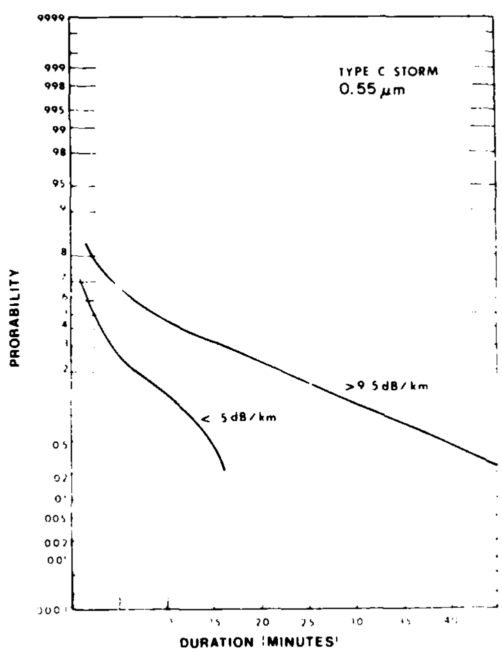


Figure 22. Observed Probability-Duration Relations During Type C Storms of Attenuation Values Less than 0.5 dB/km and Greater than 9.5 dB/km for Wavelength = 0.55 μm

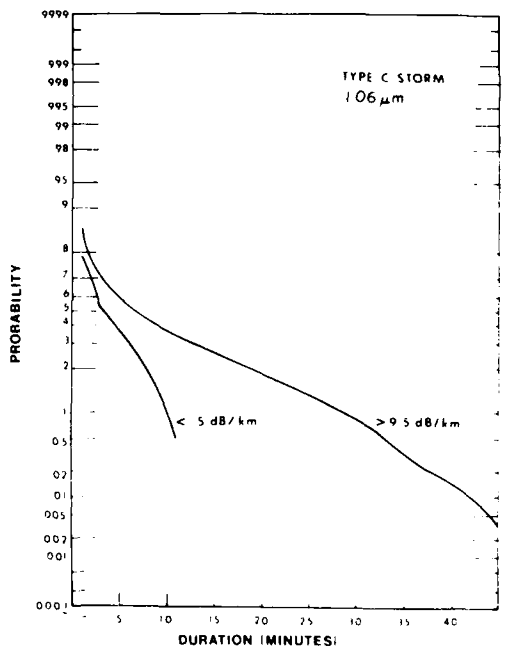


Figure 23. Observed Probability-Duration Relations During Type C Storms of Attenuation Values Less than 0.5 dB/km and Greater than 9.5 dB/km for Wavelength = 1.06 μm

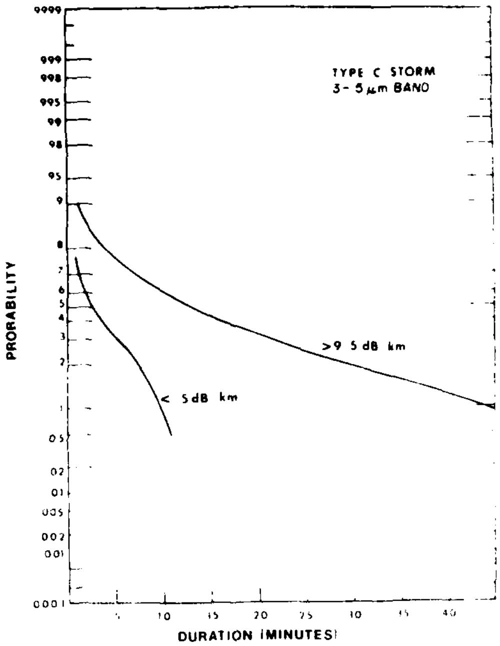


Figure 24. Observed Probability-Duration Relations During Type C Storms of Attenuation Values Less than 0.5 dB/km and Greater than 9.5 dB/km for the 3-5 μm Band

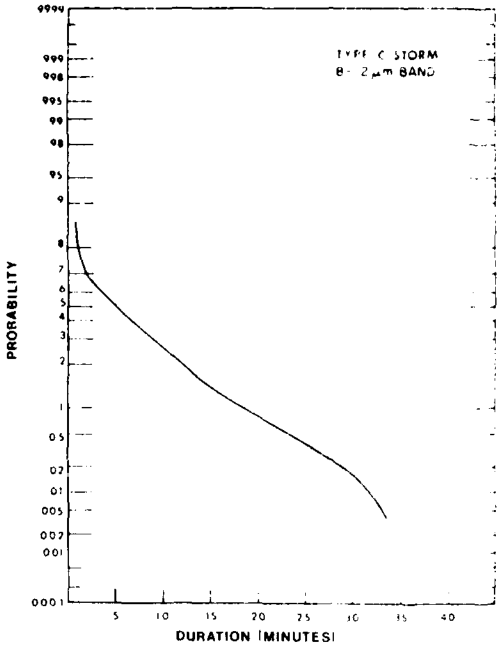


Figure 25. Observed Probability-Duration Relations During Type C Storms of Attenuations Less than 0.5 dB/km for the 8-12 μm Band

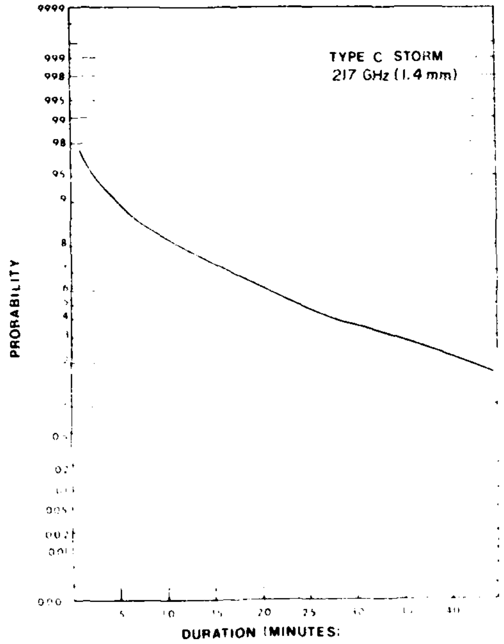


Figure 26. Observed Probability-Duration Relations During Type C Storms of Attenuations Less than 0.5 dB/km for 217 GHz (1.4 mm)

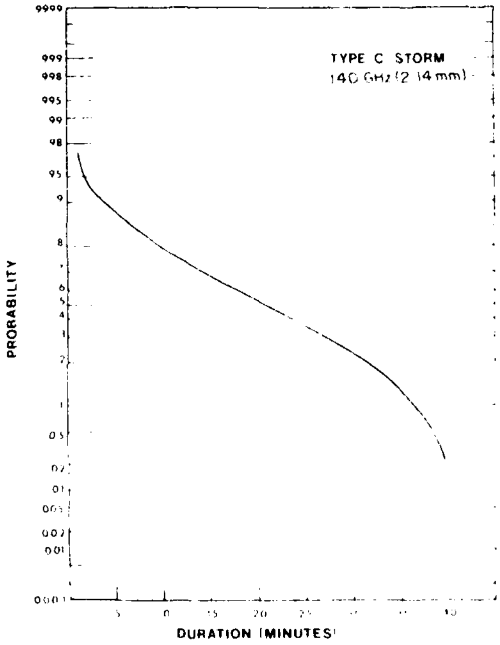


Figure 27. Observed Probability-Duration Relations During Type C Storms of Attenuations Less than 0.5 dB/km for 140 GHz (2.1 mm)

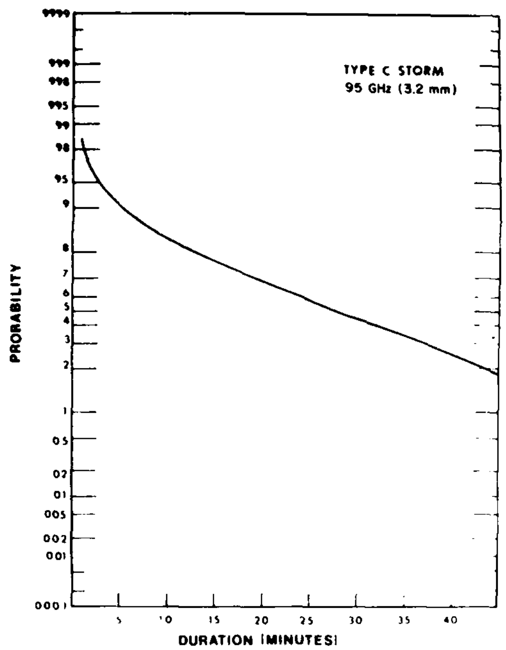


Figure 28. Observed Probability-Duration Relations During Type C Storms of Attenuations Less than 0.5 dB/km for 95 GHz (3.2 mm)

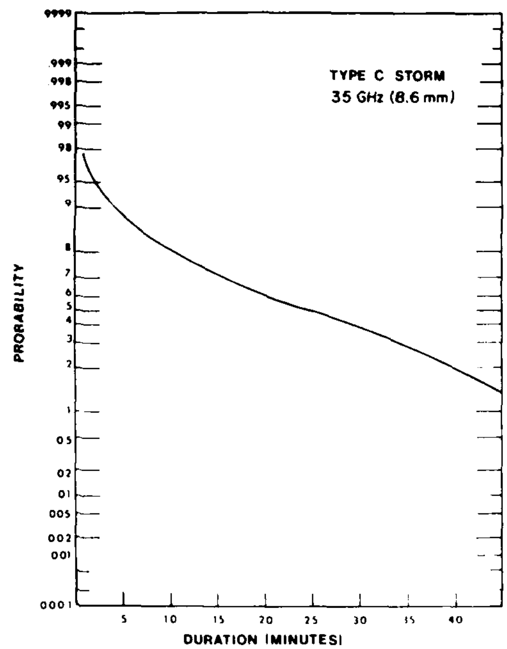


Figure 29. Observed Probability-Duration Relations During Type C Storms of Attenuation Less than 0.5 dB/km for 35 GHz (8.6 mm)

3. APPLICATION OF THE DURATION MODEL

The previous section demonstrates that it is reasonable and possible to assume that the variation in transmission levels during a snowfall behaves as a Markov chain, and to compute the probability of the attenuation reaching a given level after a given time. The model defines the conditional probability that the given attenuation level will not fall below (or exceed) a specified threshold within a specified duration. The computation time involved in deriving these probabilities for all possible cases is prohibitive. Neither would it be practical to require a commander to perform the necessary computations in the field.

Nevertheless, the model can be applied to specific cases. As an example, the model will be applied to a weapons system operating in the 8-12 μm band, for which the critical permissible attenuation is 5 dB/km. Analyzing the SNOW-ONE-A data, we obtain the following unconditional probabilities of good transmission (attenuation less than 5 dB/km).

Type A	0.58
Type B	0.75
Type C	0.19

We have already demonstrated that the transmission levels vary as a Markov chain in the 8-12 μm band. Therefore, if P_G is the 1-min autocorrelation coefficient for the less than 5 dB/km case, and P_B is the corresponding coefficient for greater than or equal to 5 dB/km case, then the probability that good transmission will continue for N minutes is $(P_G)^N$, and the probability that the transmission will improve from bad to good at the end of N minutes is $1 - (P_B)^N$.

Analysis of the SNOW-ONE-A data yields the following autocorrelation coefficients:

Type	P_G	P_B
A	0.96	0.96
B	0.96	0.80
C	0.93	0.94

The theoretical results obtained from this probabilistic model are compared with the actual data in Figures 30-35. As might be expected, the model agrees very well with the data for which it was derived. The curves are very similar with the exception of the duration of high attenuations in Type B storms. Physically, this can be explained if the instances of high snow density, causing the high attenuations, result from wind gusts. The wind gusts are of short duration, and at all other times, the snow density (and hence, the attenuations) vary exactly as they do during Type A storms. During Type C storms, in contrast, the probability of poor transmission is high, and the poor transmission tends to persist over long periods of time.

4. CONCLUSIONS

The model presented here must be derived for each frequency of interest and each critical attenuation level. Once that is done, the model is extremely straightforward and easy to use. It agrees well with the individual data sets from which it was derived. The true test of this model is to have specific autocorrelation coefficients derived from the SNOW-ONE-A data, then applied to other tests at other locations.

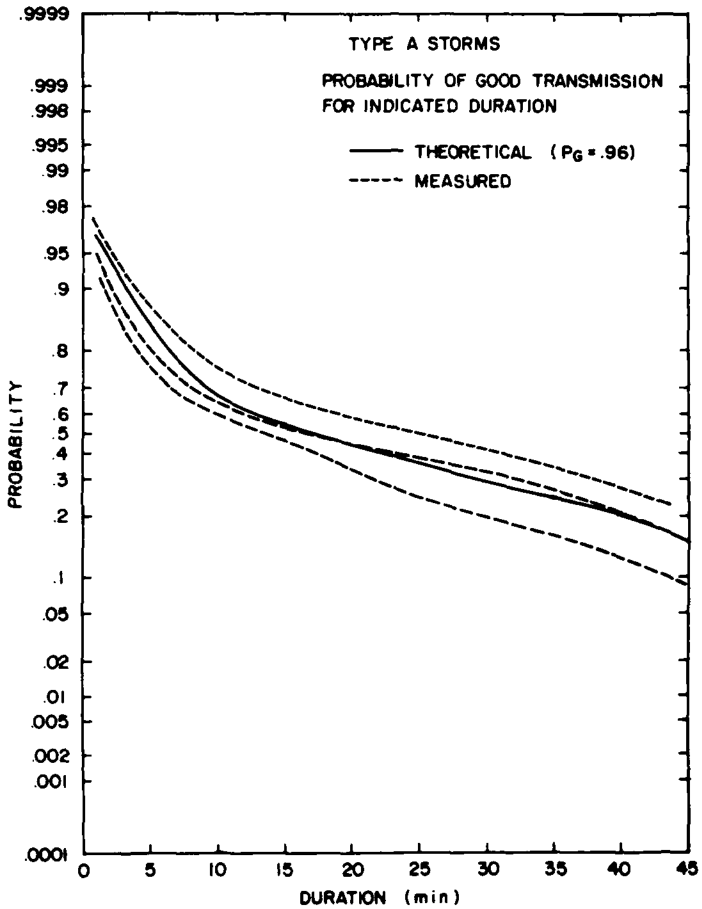


Figure 30. Probability-Duration Curves of Good Transmission for a Hypothetical System Operating in the 8-12 μm Band During a Type A Storm. Dashed lines are derived from measurements, and the solid line is based on the assumption of a Markov chain, with 1-min autocorrelation coefficient = 0.96

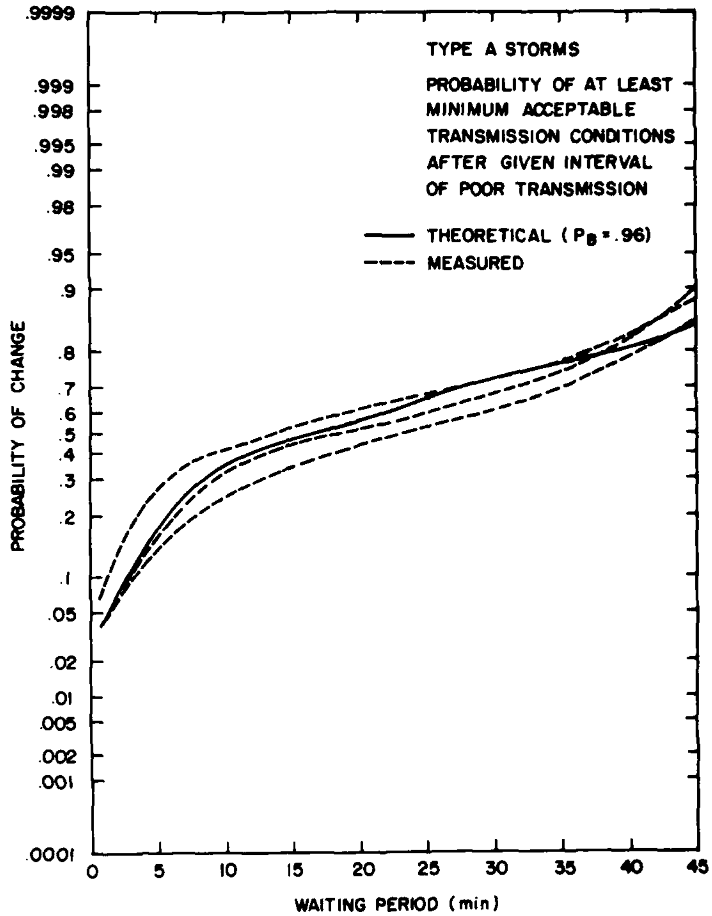


Figure 31. Inverse Probability-Duration Curves of Unacceptable Transmission for a Hypothetical System Operating in the 8-12 μm Band During a Type A Storm. Dashed lines are derived from measurements, and the solid line is based on the assumption of a Markov chain with 1-min autocorrelation coefficient = 0.96

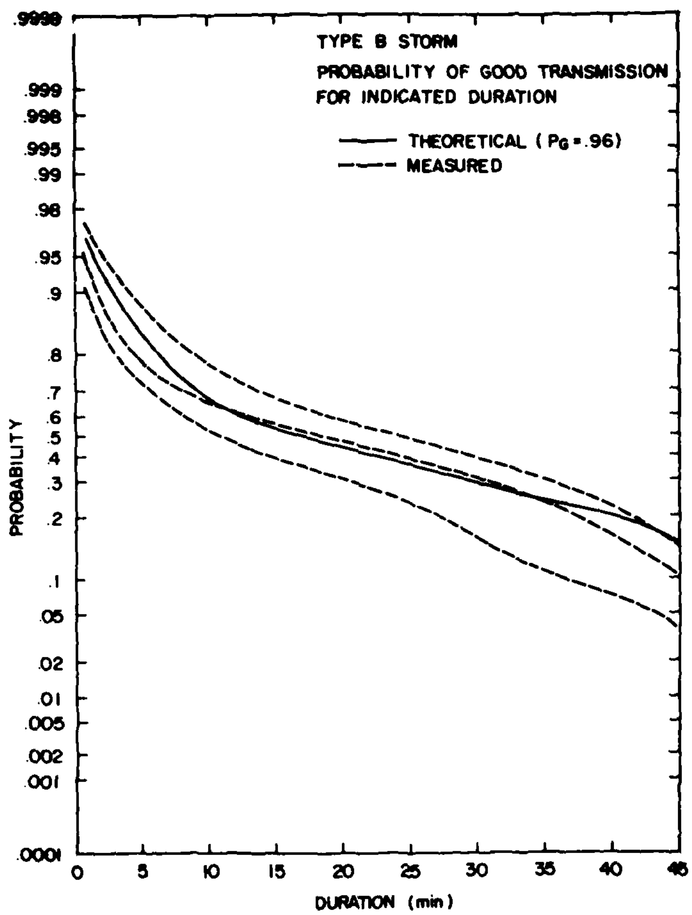


Figure 32. Probability-Duration Curves of Good Transmission for a Hypothetical System Operating in the 8-12 μm Band During a Type B Storm. Dashed lines are derived from measurements, and the solid line is based on the assumption of a Markov chain, with 1-min autocorrelation coefficient = 0.96

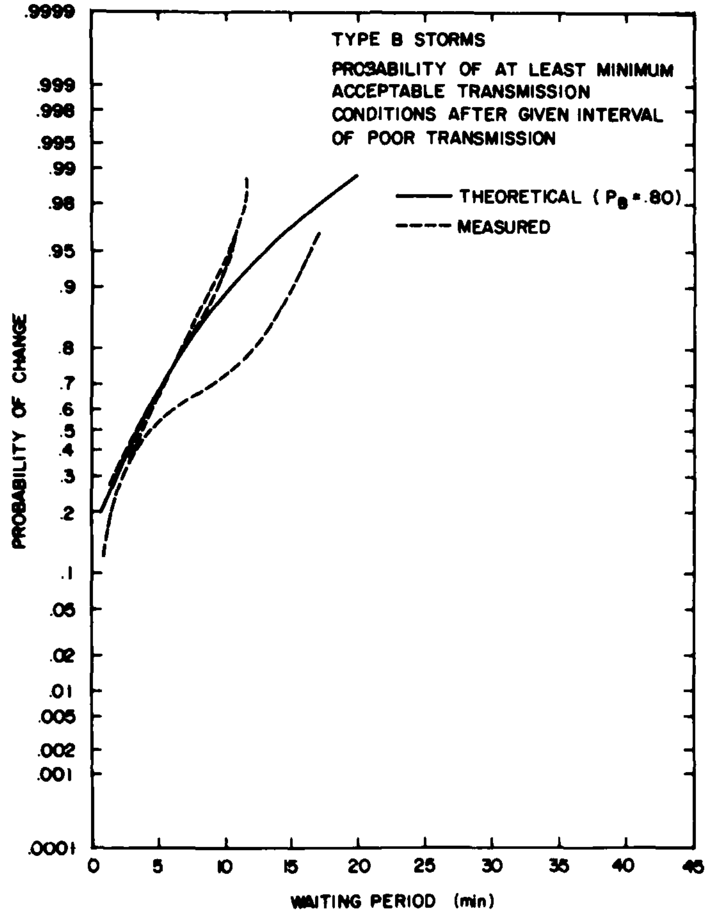


Figure 33. Inverse Probability-Duration Curves of Unacceptable Transmission for a Hypothetical System Operating in the 8-12 μm Band During a Type B Storm. Dashed lines are derived from measurements, and the solid line is based on the assumption of a Markov chain with 1-min autocorrelation coefficient = 0.80

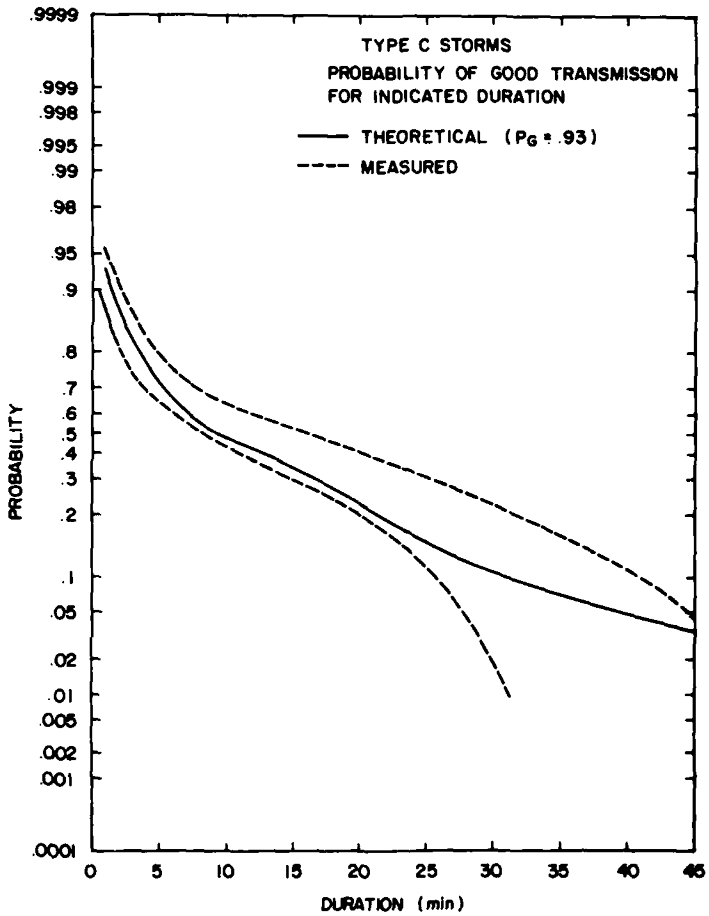


Figure 34. Probability-Duration Curves of Good Transmission for a Hypothetical System Operating in the 8-12 μm Band During a Type C Storm. Dashed lines are derived from measurements, and the solid line is based on the assumption of a Markov chain, with 1-min autocorrelation coefficient = 0.93

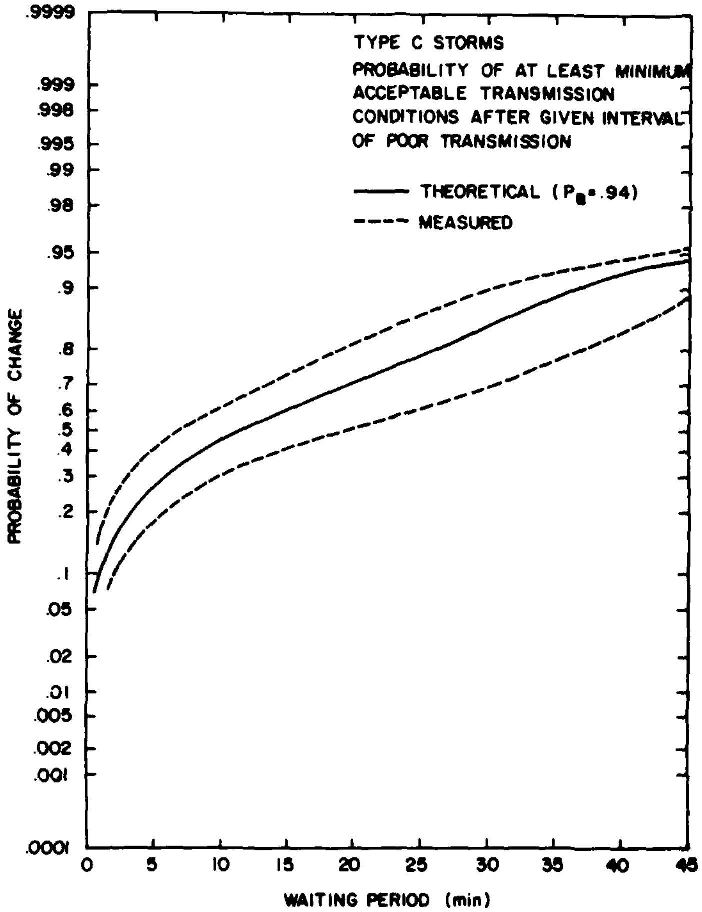


Figure 35. Inverse Probability-Duration Curves of Unacceptable Transmission for a Hypothetical System Operating in the 8-12 μm Band During a Type C Storm. Dashed lines are derived from measurements, and the solid line is based on the assumption of a Markov chain with 1-min autocorrelation coefficient = 0.94

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